Relationships Between Simple Gait Parameters of Healthy Adults and Pre- and Post-Total Knee Arthroplasty Patients

Undergraduate Honors Thesis

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Abstract

The way that people walk can change as a function of age and the progression of disease. Previous research has shown that older people tend to walk with a slower speed, exert more control at the hip joint, and exhibit reduced control at the knee and ankle joints. The onset of knee osteoarthritis (OA) causes muscle weakness and knee instability, and results in a decreased knee range of motion in OA patients. Advanced cases of OA require a total knee arthroplasty (TKA) in attempt to restore original joint anatomy, but suboptimal outcomes are very common, and leave patients with remaining knee instability and walking abnormalities. Current gait analysis requires the use of expensive motion capture technology systems and many measurement tools to achieve the desired data. A more simplified method of data collection and analysis is desired to streamline gait analysis and compare various populations. The purpose of this study was to apply a single, simplified metric to identify the differences of gait between older healthy adults and patients with OA, before and after TKA. Using existing motion capture data from each of these populations, the trajectory of the toe was plotted with respect to a fixed reference point of the hip, forming a shape that resembles an ellipse. These plots were analyzed for each population using their respective length, area, and angles. The footpath characteristics were correlated to patient-reported outcome surveys (KOOS) and a clinical outcome measure of 6-minute walking distance (6MW). Comparisons between patient populations revealed no significant relationships between footpath trajectory characteristics amongst cohorts. However, those patients who improved after surgery walked with a footpath that was longer in length and more parallel to the ground than before surgery. Additionally, larger length and angle values showed positive correlations

with better functionality outcomes, suggesting that longer strides are a more desirable gait feature. Still, due to a lack of significant results, the applied metrics may be too simple to be used as accurate tools to classify patient functionality in OA/TKA. Future work should investigate the metrics of footpath in other populations, such as younger healthy adults or patients with other neurological diseases, and explore other ways to simplify gait analysis. Establishing simple measurements to characterize the differences of gait between patient populations can give healthcare professionals a tool to concentrate rehabilitation techniques based on current patient condition.

Acknowledgements

I would first like to thank my advisor, Dr. Siston. Having the opportunity to work under him in the NMBL has allowed me to realize my academic and career goals and gain the skillset and confidence needed to pursue them. I am thankful for his constant support and encouragement through stressful school weeks, time spent abroad, and everything in between. He has pushed me to grow as a student and as a person, and I look forward to continuing my research and education under his guidance.

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Chapter 1

1.1 Background

The daily task of human walking has been the focus of research for decades. Many studies have shown that the gait cycle can change as a function of aging and the progression of disease as people must find ways to compensate for the presence of pain and variations in muscle capability [1-4]. Gait is also affected by the performance of surgery as a treatment for disease. Current analyses of gait patterns use an extensive number of variables to compare this movement in various populations. Complex motion capture systems are used to quantify these gait patterns to compare this movement between populations. It is desirable to establish a simplified metric extracted from motion data to identify differences in gait patterns.

1.1.1 Older Adult Gait

As humans age, many physical aspects of their bodies change, including muscle strength and joint stability. These changes have been seen to hinder the physical capabilities of the older population, and affect daily tasks that are necessary for independence, such as walking and stair climbing [5, 6]. When compared to the healthy younger population, older healthy adults have been shown to walk with slower gait speeds and altered joint kinematics and kinetics [7, 8]. Research has repeatedly shown that older adults have decreased strength in the hamstrings [9], along with reduced ankle plantarflexion power, which directly impacts the effect of push-off during gait [6, 9, 10]. Because of this decrease in muscle strength, the older adult population must accommodate for ankle weakness by relying more on the hip joint for forward movement [9]. This accommodation has been shown to result in an increase in hip extension torque and hip power generation, along with a decrease in hip flexion torque [1]. Many researchers have explained these gait alterations as a strategy to compensate for the muscle weakness and instability that progresses with age [10, 11]. However, abnormal walking patterns of the older adult population can accelerate the wear and tear that the knee joint experiences, which have been related to the progression of diseases such as osteoarthritis [12].

1.1.2 Osteoarthritic Patient Gait

Knee osteoarthritis (OA) is a degenerative joint disease caused by the breakdown of cartilage between the bones of the knee (see Figure 1), and affects over 30 million US adults [13].

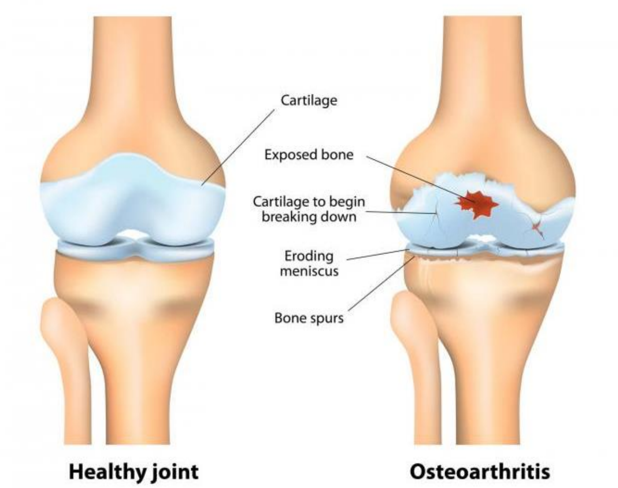

Figure 1: Features of Osteoarthritis [14]

Some characteristics of OA include pain, stiffness, a decreased range of motion, and swelling of the affected joint. These symptoms can cause reduced function and disability of the knee and greatly inhibits the capability of patients to perform daily activities [13].

People with OA have been shown to alter their gait to accommodate for the pain and joint instabilities that accompany this disease. OA patients experience reduced strength in the muscles that cross the knee, along with an imbalance between their knee flexors and extensors [15]. Those affected by OA have been shown to walk with slower velocities, a shorter stride length, and spend more time in the stance phase of gait [16, 17]. They also exhibit a significantly decreased knee range of motion [4, 17, 18], decreased knee flexion [3, 15, 16, 18], and an increase in muscle co-activation [4, 15]. Many of these alterations can be attributed to the attempt of stabilizing the arthritic knee during the weight acceptance phase of gait, which is often referred to as a “stiff-knee” gait pattern [4, 15]. Due to the differences between the affected and unaffected joint movements, OA patient gait often becomes asymmetric, which can cause more symptoms to develop or worsen [3]. Severe cases of OA require joint replacement surgery in attempt to alleviate pain and return patients to a normal quality of life.

1.1.3 Gait After Total Knee Arthroplasty

The most common end stage treatment for OA is the performance of a total knee arthroplasty (TKA), which is one of the most commonly performed orthopedic procedures in the United States [7]. In this operation, the surgeon removes damaged cartilage and bone from the surface of the knee joint and replaces them with the appropriate prosthetic devices to rebuild original joint anatomy (see Figure 2) [19].

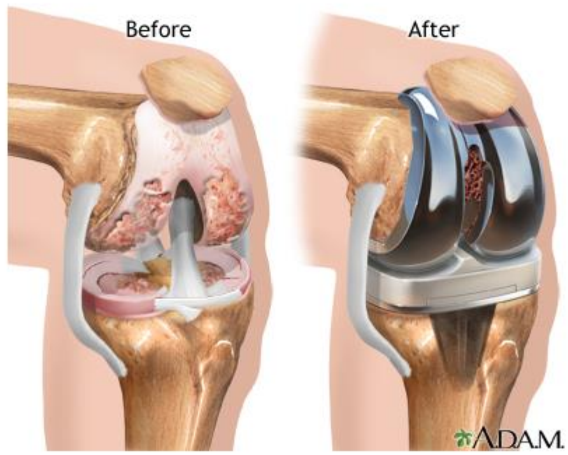

Figure 2: TKA Implant [19]

An estimated 693,400 TKAs were performed in 2010, and the rate of TKA operations is expected to continue to increase [3]. Because the prevalence of this procedure is growing, the desire to achieve positive surgical outcomes is becoming more imperative for both patients and surgeons [20].

While the end goal of a TKA is to restore full knee function and return the patient back to a healthy quality of life, many patients experience suboptimal outcomes post-surgery. Abnormal gait patterns that are present pre-operatively often remain after surgery, even when knee pain is reduced [8, 21]. The range of motion of the knee joint is also often still reduced post-operatively [22]. Though the physical sources of OA pain are corrected with surgery, irregular muscle co-activation patterns are often still present,. These gait characteristics of TKA patients serve as evidence that even after surgery, daily capabilities are still inhibited.

1.1.4 Functional Outcome Measures

Patient function is measured in many ways in clinical research, both patient-reported and performance-based. One common self-reported functional measure is the Knee Injury and Osteoarthritis Outcome Survey (KOOS), which consists of various sub-scales regarding how patients view the condition of their knee with respect to different circumstances [23]. The 6-Minute Walk (6MW) test is another clinical measure that records how far a patient can walk in a timed 6-minute interval [24]. These measures can be collected both pre- and post-operatively to give clinicians more information on how patient functionality changes over time throughout their disease or surgical process.

Many studies that have recorded both of these functional measures in the OA/TKA population have indicated that it is common for patients to function poorly even after undergoing surgery. Others have shown that outcomes initially worsening after surgery have improved over time [25, 26]. However, many TKA patient KOOS scores are not significantly improved from their self-reported scores pre-operatively [27]. Additionally, patients following TKA still perform significantly worse in the 6MW test than healthy controls, indicating that the performance of surgery is unable to return them to full function.

1.2 Analyzing Gait Changes

While the activity of human gait has been thoroughly documented and analyzed by many research studies, the extensive number of variables and metrics that result from these studies can cause confusion when trying to make simple comparisons between patient populations. Additionally, the technology currently utilized to capture motion data that is used in gait analysis requires extensive and expensive equipment and software tools to extract the desired data. It would be beneficial to have a simplified way of collecting gait data without the need for an established motion capture lab, for example, the use of a camera on an everyday smart phone.

It has been hypothesized that in the task of gait, the underlying goal of the nervous system is to simply control the movement of the foot [28]. If every individual metric of gait (e.g., joint kinematics) could be consolidated and viewed to be contributing to this one ultimate intention of the body, then only one metric could be used as a simple measure to gain insight into an individual's gait pattern.

Dr. Yuri Ivanenko explored this idea by creating a visual representation gait, which he defined as the trajectory of the path of the foot relative to the pelvis. He introduced this concept of footpath trajectory when examining how gait changes with varying speeds and levels of body weight support [28]. His study created a footpath "ellipse" by plotting the position of the toe with respect to a fixed origin at the hip throughout the gait cycle, and superimposed this for multiple steps taken by each subject (see Figure 3). The resulting ellipse-like shape was then analyzed based on characteristics such as overall horizontal and vertical excursion, as well as the mean area enclosed by the trajectory over each trial [28].

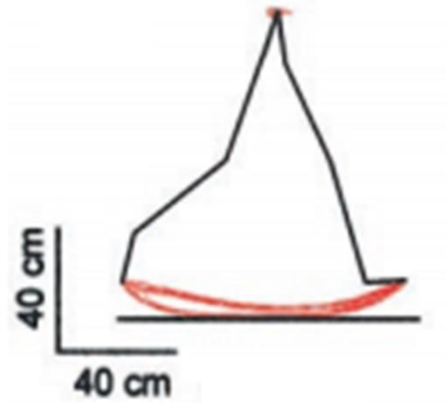

Figure 3: Footpath Ellipse from [25]

There are some limited applications of footpath trajectory in current literature involving gait variations, such as walking versus running, toddler walking stability, and recovering spinal cord injury patients [28-30]. However, there is the potential to extend this method of analysis to study many more categories of populations. It is possible to apply this visual representation of the control of gait to study how the footpath trajectory changes with the presence of disease and the completion of surgery. Therefore, the purpose of this study is to analyze the differences in gait between older healthy adults, patients with osteoarthritis, and post-TKA patients using footpath trajectory.

The resulting graphical metric could have the potential to represent the holistic activity of gait for each group of subjects, which can then be examined to detect common characteristics that apply to the entire population. By comparing the footpath trajectory between populations, differences in gait patterns could be identified. Ultimately, these patterns may lead to the design of a diagnostic tool to quickly analyze the condition of patients and determine where they lie on a spectrum of functionality. From this, healthcare professionals could be able to use this tool to focus rehabilitation techniques in order to best treat each individual patient dependent upon their condition.

1.3 Focus of Thesis

The focus of this research was to explore footpath trajectory in various populations and analyze different metrics of this footpath. This was accomplished by importing motion capture data from Vicon into MATLAB and modeling the position of the toe relative to the hip. The resulting trajectory was then evaluated for each subject and compared among cohorts, allowing conclusions to be drawn about footpath trajectory characteristics for each respective patient population. The different footpath metrics were also analyzed with respect to measures of patient functionality in the OA and TKA groups to determine if they could also relate to patient outcomes pre- and post-surgery.

1.4 Significance of Thesis

Though there is currently a large number of research studies comparing gait between populations, analyzing gait differences amongst these populations can be complex due to the amount of metrics that are measured and analyzed. Being able to evaluate patient gait using the simple tool of footpath trajectory could lead to a more streamlined patient analysis and development of more efficient techniques for physicians to characterize and treat their patients.

Chapter 2: Methods

2.1 Data Collection

Data for this investigation was collected from three different subject populations. The older healthy (OH) population was comprised of 13 subjects (6 male, 7 female, age = 62.8±5.4 years, height = 1.74±.08 m, mass = 71.0±10.8 kg). The OA/TKA population included twenty-two subjects (7 male, 15 female, age=60.6±6.8 years, height=1.66±0.86 m, mass=92.9±16.5 kg). This subject group came into the lab at three different time periods: pre-operatively, forming the OA population, as well as 6-months (6MO) and 24-months (24MO) post-operatively, categorized as the TKA population. All subject groups provided written informed consent in accordance with the Institutional Review Board of The Ohio State University to participate in this study.

Experimental motion data was collected by previous studies in the Motion Analysis and Performance Lab by Dr. Elena Caruthers, Rachel Baker, Greg Freisinger, Jacqueline Lewis, and Sarah Roelker. Motion data were collected at 150 Hz using a 10-camera Vicon MX-F40 system (Vicon: Oxford, UK) and filtered using a fourth-order Butterworth filter at 6 Hz. The lower limbs were tracked with a modified Point Cluster Technique, which included additional markers on the iliac crests [31]. The upper limbs and torso were tracked with markers placed on bony landmarks (Figure 4a) [32]. Each OH subject completed 3 consecutive gait trials and each OA/TKA subject completed 5 trials, all at a self-selected speed, as well as a hip joint center (HJC) calibration. These HJC trials were analyzed to estimate the location of the center of the hip (Camomilla, Cereatti et al. 2006). Subjects in the OA/TKA population also completed the Knee Injury and Osteoarthritis Outcome Survey (KOOS) [23] and the 6 Minute Walk (6MW) test [24] to establish performance-based and self-reported functionality.

2.2 Data Processing

Motion capture data that were collected for each trial were processed in a program known as Vicon Nexus. Markers for each trial were labeled, and any gaps in these markers were filled by applying either spline fill or pattern fill with a marker of similar trajectory. After every gait trial was processed, they were exported into MATLAB (Mathworks, Inc., Natick, MA). The locations of the markers on the 5th metatarsal and the greater trochanter were extracted (Figure 4b).

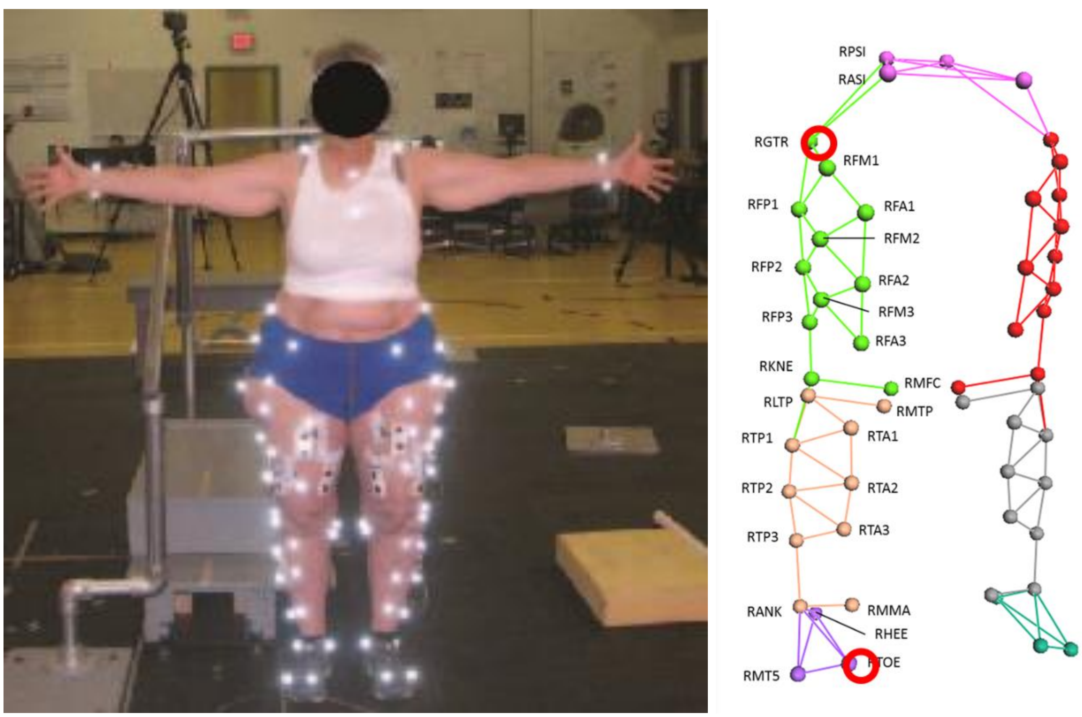

Figure 4: Motion analysis modified point-cluster marker set (a) on subject and (b) in Vicon

By tracking the horizontal location versus vertical location of the toe marker with respect to the hip, the footpath trajectory for each trial was plotted. This trajectory data were normalized according to subject height. The resulting footpath trajectory was evaluated according to length, angle, and area. The length was defined as the maximum distance of horizontal displacement, representing maximum toe excursion. Additionally, the angle of the footpath was extracted from the points of maximum horizontal displacement. The angle was defined as that which was formed between the line connecting these two points with respect to the horizontal axis (see Figure 5).

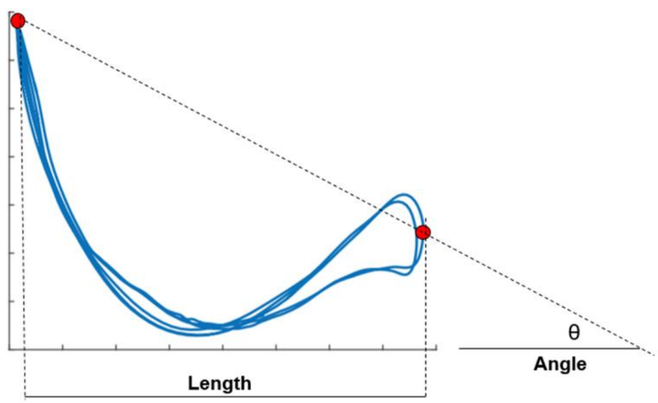

Figure 5: Footpath length and angle definitions

Preliminary analysis applied a best-fit ellipse to the data to calculate area and angle with respect to the horizontal. However, upon further analysis, it was determined that this metric was not representative of the true footpath shape (see Figure 6).

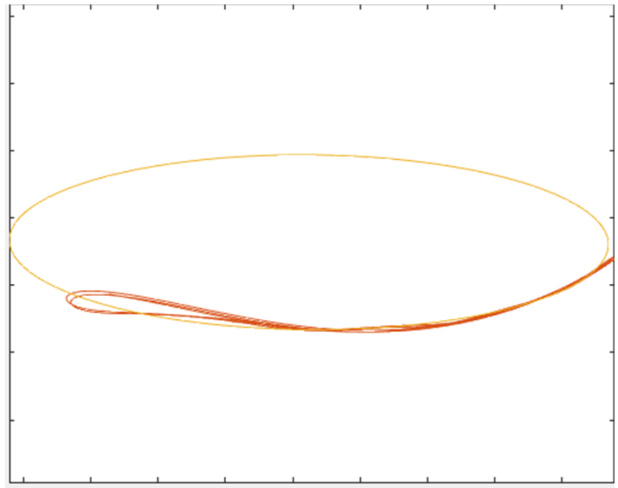

Figure 6: Inaccurate initial area calculation from ellipse function

The area enclosed by the path of the foot was then modified to be defined by application of trapezoidal integration. The total footpath trajectory was first separated into consecutive stance and swing phases. The area under each of these phase curves was separately calculated according to trapezoidal integration, and the area of each gait cycle was found by subtracting the area for the stance phase from the area of the corresponding swing phase. If one trial contained multiple gait cycles, these resulting areas were averaged to determine the final footpath area (see Figure 7).

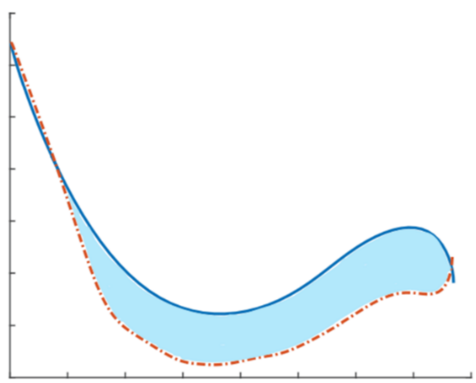

Figure 7: Improved footpath area representation using trapezoidal integration

2.3 Data Analysis

Two-sample t-tests were used to compare the three footpath characteristics (length, area, and angle) between the older healthy and OA/TKA populations. Significant differences were defined as those tests whose p-value was less than 0.05. An F-test for equality of two-variances was completed for each measure to analyze the differences in variability among subject populations.

A repeated measures analysis of variance was used to determine the differences in the footpath characteristics at the different time points before and after surgery for the OA/TKA patients. Post-hoc tests were performed as appropriate. Because the Activities of Daily Living (ADL) and Quality of Life (QOL) KOOS sub-scale scores were non-normally distributed, Spearman's rho was applied to identify how the footpath characteristics were related to these sub-scales. Additionally, the 6-minute walk (6MW) distances were normally distributed; therefore, Pearson's correlations were used to relate these distances to the footpath characteristics.

Chapter 3: Results

3.1 OH vs OA/TKA

The average non-dimensional footpath length of the OH population (0.445±0.031) was significantly larger than that of the OA population (0.361±0.16, p=0.022), but was not different than the length of patients at 6-months (0.421±0.11, p=0.303) or 24-months post-TKA (0.411±0.11, p=0.165). The average lengths of the OH population were significantly less variable than those of the OA (p<0.001) and 6-month post-TKA (p=0.036), but not than 24-months post-operation (p=0.055).

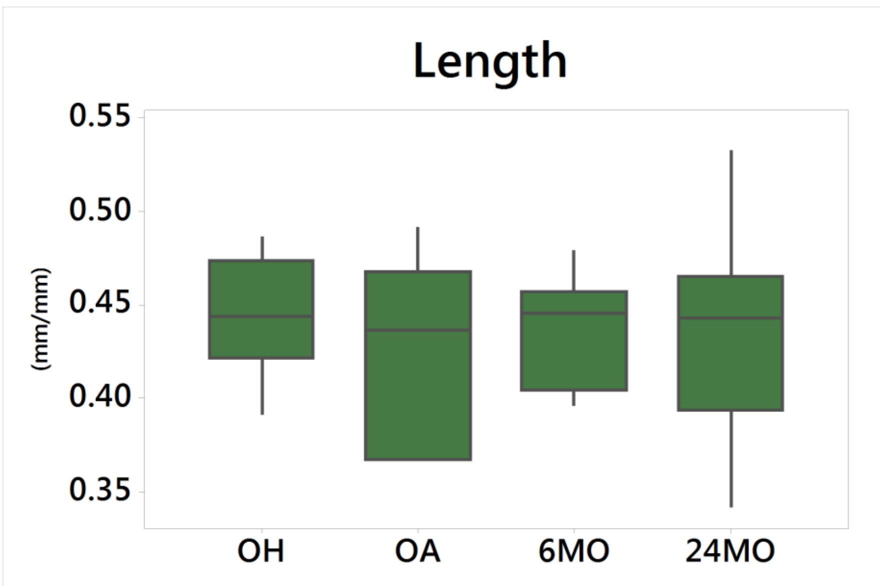

Figure 8: Trends of footpath length among each population. There were no significant differences observed between subject populations.

The OH population displayed an average non-dimensional footpath area (0.327±0.11) that was significantly smaller than that of the 6-month post-TKA group (0.390±0.11, p=0.047). However, this value was not significantly different from the OA (0.334±0.17, p=0.930) or 24-month post-surgery population (0.376±0.027, p=0.165). The

OA population areas were significantly more variable than those of the OH population (p=0.012), although this relationship was not significant among other subject cohorts.

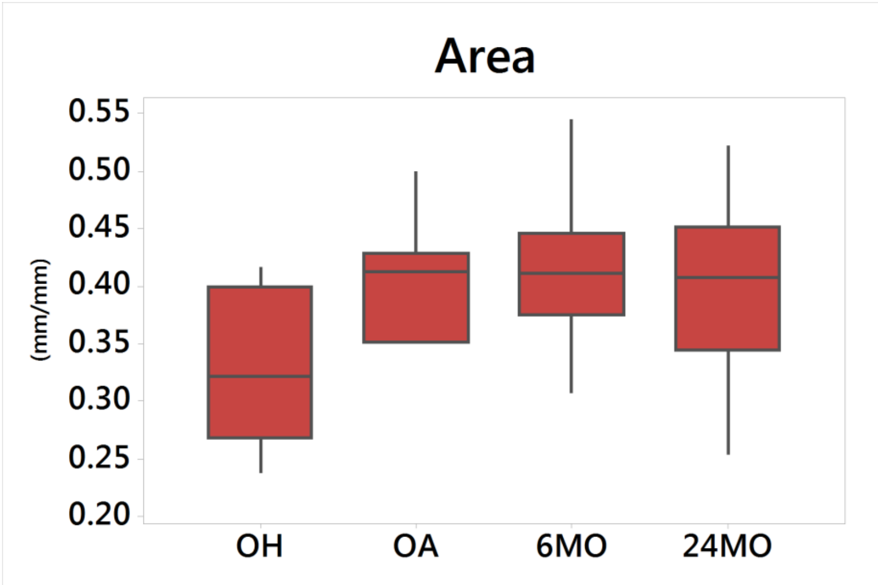

Figure 9: Trends of footpath area for each population. There was a significant difference of the OH population from OA/TKA, with no other significant differences.

The average footpath angles trended to be smallest in the OH population (6.40±1.3°), and largest in the OA group (9.91±2.1°), although these relationships fell short of statistical significance. These values decreased slightly with time after surgery, with average angles of 7.99±1.2° at 6-months and 7.23±0.65° at 24-months post-operation. Two-variance analysis revealed that the OH population demonstrated footpaths whose angles were significantly less variable than the OA group (p=0.010) and significantly more variable than the 24-month post-TKA (p=0.038) group.

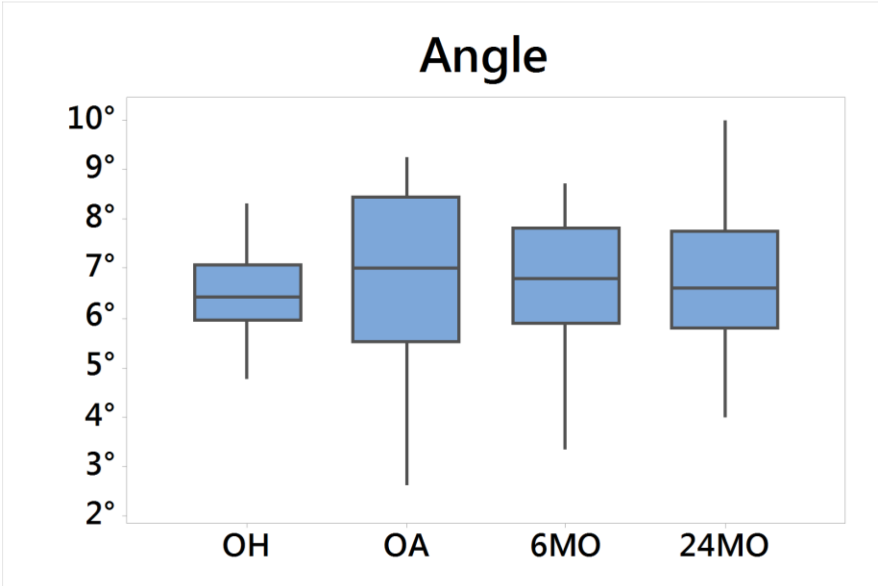

Figure 10: Trends of footpath angle for each population. There were no significant differences between any of the populations.

	Length		Area		Angle	
OH	0.445 ± 0.03	-	0.327 ± 0.11	-	6.40 ± 1.3°	-
OA	0.361 ± 0.16	**p = 0.022**	0.334 ± 0.17	p = 0.930	9.91 ± 2.1°	p = 0.098
		p* = 0.028		**p* = 0.035**		p* = 0.342
6MO	0.421 ± 0.11	p = 0.303	0.390 ± 0.11	**p = 0.047**	7.99 ± 1.2°	p = 0.169
		p** = 0.190		p** = 0.327		p** = 0.558
24MO	0.411 ± 0.11	p = 0.154	0.376 ± 0.03	p = 0.165	7.23 ± 0.7°	p = 0.183
		p† = 0.675		p† = 0.617		p† = 0.246

Table 1: Footpath characteristics and comparisons between all populations. Significant p-values are displayed in bold. (*) = OA vs 6MO; (**) = 6MO vs 24MO; (†) = OA vs 24MO.

3.2 OA/TKA Patients over Time

Repeated measures analysis of variance was used to determine differences in footpath characteristics in patients before and after surgery. This analysis revealed that average footpath length of the OA population was significantly smaller than that of the 6-

month post-TKA group (p=0.028) but did not differ from the 24-month cohort (p=0.190). Additionally, there was no significant difference between average lengths of post-TKA patients from 6 to 24 months (p=0.675).

Applying the same analysis revealed that the average area of OA patients was significantly greater than that of the 6-month post-TKA cohort (p=0.035), but no other significant differences in patient time points were found. Additionally, rm-ANOVA showed no significant differences in footpath angle for any time points. However, post-hoc analysis displayed insignificant differences in any of the footpath characteristics across all time points.

3.3 Measures of Patient Performance

The 6-Minute Walk test was significantly related to some footpath characteristics amongst the different patient populations. Longer ellipse lengths and larger areas were significantly associated with a greater 6MW distance pre-operatively (r=0.640, p=0.001; r=0.623, p=0.001) and at 6 months post-operation (r=0.537, p=0.008; r=0.494, p=0.016). However, this relationship was not significant at 24 months post-operatively (r=0.323, p=0.143; r=0.276, p=0.214).

OA	Length		Area		Angle	
6MW	r = 0.640	**p = 0.001**	r = 0.623	**p = 0.001**	r = -0.255	p = 0.239
ADL	ρ = 0.440	**p = 0.035**	ρ = 0.333	p = 0.120	ρ = -0.325	p = 0.131
QOL	ρ = 0.318	p = 0.139	ρ = 0.206	p = 0.347	ρ = -0.189	p = 0.389

Table 2: Correlation values between OA footpath characteristics and outcome measures.

6MO	Length		Area		Angle	
6MW	r = 0.537	**p = 0.008**	r = 0.494	**p = 0.016**	r = -0.229	p = 0.293
ADL	ρ = 0.141	p = 0.520	ρ = 0.166	p = 0.450	ρ = -0.031	p = 0.889
QOL	ρ = 0.101	p = 0.645	ρ = 0.087	p = 0.692	ρ = 0.068	p = 0.759

Table 3: Correlation values between 6MO footpath characteristics and outcome measures.

24MO	Length		Area		Angle	
6MW	r = 0.323	p = 0.143	r = 0.276	p = 0.214	r = 0.152	p = 0.498
ADL	ρ = 0.275	p = 0.204	ρ = 0.273	p = 0.207	ρ = -0.038	p = 0.864
QOL	ρ = 0.353	p = 0.099	ρ = 0.334	p = 0.120	ρ = 0.413	p = 0.413

Table 4: Correlation values between 24MO footpath characteristics and outcome measures.

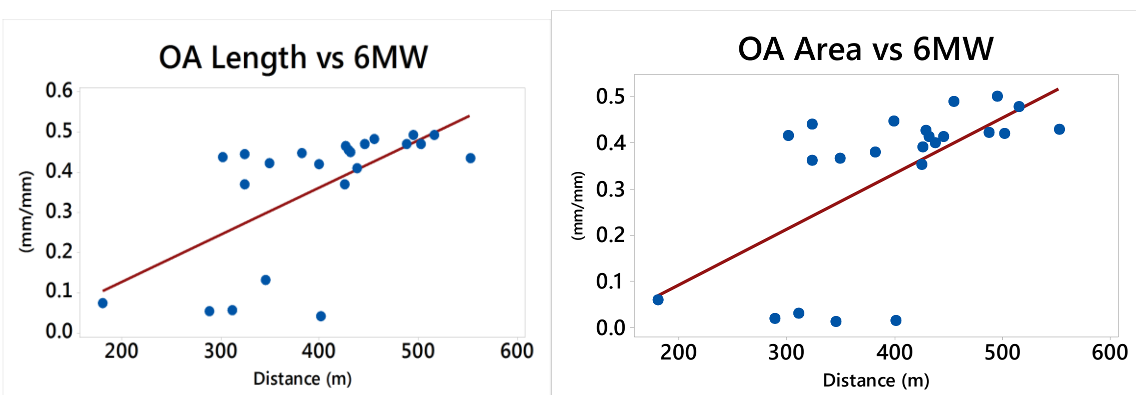

Figure 11 a-b: Significant relationships of OA footpath (a) length and (b) area to 6MW distances.

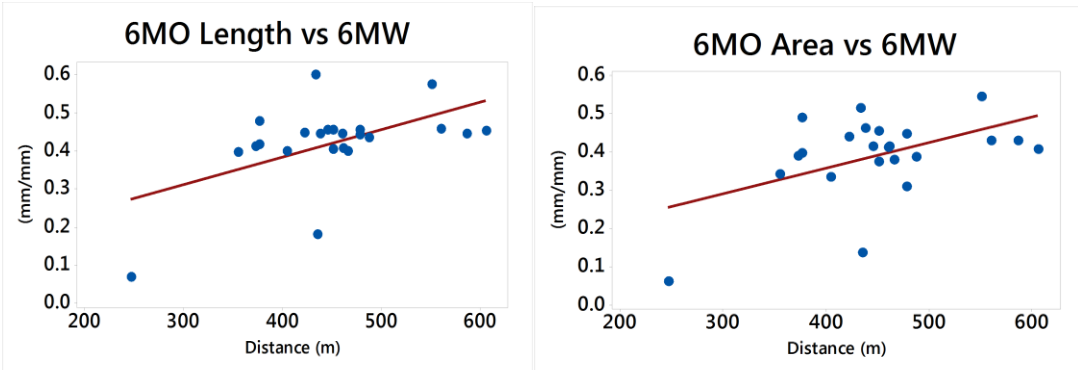

Figure 12 a-b: Significant relationships of 6MO footpath (a) length and (b) area to 6MW distances.

Pre-operatively, longer ellipse length was related to a better KOOS ADL sub-scale score ($\rho=0.440$; $p=0.035$) (Figure 13). However, there were no significant relationships to KOOS sub-scales in either category at 6-months and 24-months post-operatively.

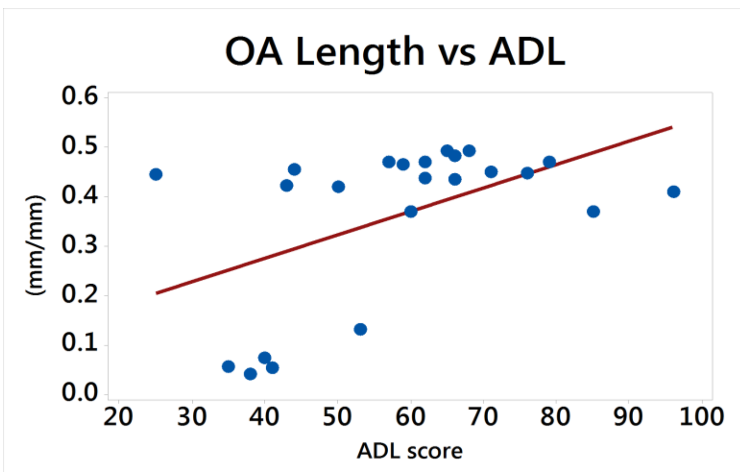

Figure 13: Significant relationship of OA footpath length to ADL score.

Chapter 4: Discussion and Conclusion

The present study was designed to explore the feasibility of using the simplified metric of the footpath to accurately classify patient functionality of different populations. While some significant relationships were observed from the chosen footpath characteristics, this basic measure may not change enough between populations to be representative of their differences. Additionally, this metric may not be related to patient function.

4.1 Footpath Characteristics

Some population trends were observed in the various measures characterizing footpath, although not every pattern showed statistical significance. The older healthy population displayed the largest footpath length, with smallest values for both area and angle, signifying a long and flat stride. Pre-operative patients showed the largest footpath angle accompanied by the shortest length, which contrasts with the typical trends of the healthy cohort. Following TKA, patient angles and areas both decreased over time, suggesting that patients began to walk with flatter and shorter steps. Additionally, patients after surgery exhibited longer strides, which is in agreement with other studies that have reported increased stride length in TKA patients when compared with pre-operative measures [21, 33].

By comparing the footpath characteristics of the older healthy population with those of the osteoarthritic and post-operation cohorts, it could be interpreted that a longer, flatter excursion of the foot is more representative of a healthy, functioning subject.

4.2 Patient Performance

Due to the lack of significant relationships between footpath measures and KOOS sub-scales, it is not possible to draw any conclusions about whether these characteristics can accurately depict patient functionality before or after surgery. However, some significant correlations between footpath length and areas with 6MW distances suggest that longer, more elongated strides are representative of subjects who can walk farther in a specified amount of time. This finding was expected, as people who display larger stride length walk with faster velocity, traveling further with each step [2].

It was anticipated that longer strides might also relate to better KOOS scores, which have been validated in many studies to accurately reflect functionality changes over time post-operatively [34, 35]. The Activities of Daily Living (ADL) score was of particular interest, as this subscale most closely relates to the Function dimension of the WOMAC Osteoarthritis Index [23]. Interestingly, this relationship was not supported by the data, which did not show significant patterns between footpath and functionality for the TKA cohorts. This result may be due to the simplistic nature of this footpath metric, which is unrepresentative of the complex biomechanical differences present in the respective subject populations.

4.3 Limitations of Study

The method of this study for analyzing footpath trajectory was completed by averaging the trajectories of each patient's individual gait cycles and then calculating their footpath characteristics. Another method of analysis could be to calculate characteristics for each singular gait cycle and then compute averages for every patient and their respective population. This technique could result in trends differing from what were found in the present study and would also express a different way of assessing the variability among patient populations.

An additional method of analysis could relate these footpath characteristics to other variables currently measured during gait, such as joint angles or moments, to observe whether they are capable of explaining the variability or patterns in these metrics.

4.4 Conclusions and Future Work

This document summarizes the results of an exploratory study designed to examine whether simplified gait metrics are capable of classifying patient functionality in different patient populations. Based on the lack of significant results in footpath characteristics and relationships with functionality measures, it cannot be confirmed that the chosen footpath metrics can accurately characterize the differences of gait patterns between the chosen subject cohorts. It could be possible that the location of the toe position relative to the hip does not provide sufficient enough information to accurately encompass the complex nature of gait, especially when considering how OA or TKA affect this motion.

However, future work could compare the same metrics with the younger healthy population to analyze whether these metrics have more applicable significance when looking solely at age differences, rather than the intricate joint changes caused by OA and TKA. The application of footpath metrics could also be explored in other patient populations suffering from neurological diseases such as stroke or Parkinson’s disease. Additionally, further studies should explore other ways to define measures that could simplify gait analysis of the current populations. Identifying a simplified method of analyzing gait patterns could serve as a beneficial tool to streamline rehabilitation techniques in a wide variety of patient groups.

In conclusion, the present exploratory study found that measures of footpath in relation to the hip are too simple to represent the complex changes that occur in gait analysis of patients before and after TKA when compared to healthy controls. More work is needed to find a sufficient alternative to current gait analysis that could lead to more simplified rehabilitation strategies in an extensive range of populations.

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